# Reducing Diesel Particulate Emissions by 99 %

# The Swiss Approach

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# The Swiss Chronicle to reduce Diesel Particulate emissions by 99 %

- Offroad Emissions Inventory 1993 / 1998
  ( computer-model for predictions now available on CD – in German)

- VERT-Project 1994-1998 to define BAT

- BUWAL: Clean Air Act Amendments 3 / 1998
  - Diesel Particulate classified as carcinogenic
    (to be minimized acc. to BAT irrespective of cost)
  - PM 10 – Limit 20 g/m3 ( exceeded in all cities)
  - Traps for construction sites in/nearby cities

- SUVA: Traps for the working place 3/2000

- Implementation Tools:
  - Trap-System Specification 1996
  - Trap-System-Certification Procedure 1997
  - Filter-List of all certified traps on the Net 1998
  - Ultrafine Particle Metrology “NanoMet” 1999
  - EC-oriented Calibration method by EAM 1999
  - Trap OBD-Systems “LogLink” 1999
  - Trap Manufacturer Association AKPF 1998
  - Nanoparticle Measurement Conference since 1997

- 2500 traps operating – controlled by field testing
  (should be 100 % yearly control – now only 10-15 %)

- STUMP-Postulat: “Retrofit of all swiss HDV-onroad with efficient filters vehicles as soon as possible”

# Swiss Offroad Emission Inventory

- Diesel-Inventory based on ca 300 engine maps 1994
  Published 1996

- Offroad Diesels emit as much PM as onroad Diesels
  Share deteriorates as onroad Diesels become cleaner by regulation and offroad not

- Offroad Diesel emission is serious local pollution
  “local climate-effect” since traffic dilution is missing
  Critical situation for construction sites in cities

- Legal Situation: Switzerland can act offroad
  whereas it is preemted to some extent from actions onroad
  for new vehicles because of EU-contracts

- Review of offroad inventory 1998 shows no improvement

- Computer model established to predict emissions for given local situations like construction sites

- Clean Air Act LRV  modified accordingly 1998

# VERT-Project 1994 - 1998

- Common project of
  Occupational Health Authorities CH/D/A
  and swiss Clean Air Authority BUWAL
  with innovative industrial partners

- Target 1 : establish BAT to reduce Diesel Particulate-Emissions to < 5 %
  applicable to all existing diesels
  using market available technology
  within 3 years

- Target 2: evaluate or develop certification procedures and field controls for the retrofit-technology

- Target 3: establish implementation tools

- Particulate Definition:
  - Solid particles: soot EC-core + adsorbed OC
  - Size range 10 – 500 nm

- Results: (all published)
  - Modern OR-Diesels emit as many particles as old engines
  - Clean Fuels do not reduce particle number emission
  - Oxi-Catalysts do not reduce particle number emission
    but increase NO2 and SO3 to unacceptable levels
  - Traps reduce particle numbers by > 95 (up to 99) %
  - Traps do not loose efficiency after 2000 hrs field test

- Specifications and test procedures
  developed with industrial partners
  accepted by German, Austrian and Swiss Occ.Health Authorities
  as well as Swiss Clean Air Authority BUWAL, German UBA and DEEP

# Definition of Diesel Particulate

or Diesel-emitted Particles ?

- **Definition with respect to Health Effect**
  Mass ? Count ? Surface ? Size (aerodynamic or mobility ?) Range ?
- **Definition regarding chemical substance**
  Or at least “leading substance”
- **Definition regarding physical appearance**
  (phase, size parameters)
- **Definition regarding sampling spot**
  (tailpipe ? engine ? anywhere ??)
- **Definition regarding sampling conditions**
  Load, speed, cycle, steady/transient ?

**Swiss Definition**: Solid Particulate (< 300°C)
and anything adsorbed to it
at tail-pipe conditions
in the size range 10-500 nm

# Legislation / Regulation

- SUVA requires Traps for underground Work
  and all closed or semi-closed rooms
  100 % application, no exceptions
  only VERT-certified traps are accepted
  in force 3/2000

- BUWAL requires Traps for Diesel at construction sites
  In cities or closeby cities
  Implementation by local government (Cantons)
  Only VERT-certified trap-systems
  Regular field control required (yearly)
  Exceptions for very short operation period
  In force 3/1998

- Trap systems must comply with other legislation
  ( noise, safety)

- Trap systems using catalytic coatings or fuel catalysts
  must prove “no emission of secondary toxic emissions”
  In force 1990

# Trap-System Specification

- Filtration Rate for Particulate Mass desirable > 80 %
- Filtration Rate for Particle Number mandatory > 95 %
- Filtration Rate for EC-Mass mandatory > 90 %
  For the fresh, loaded and regenerated trap
  the new and old trap (old = 2000 hrs of field operation)
  also transient during regeneration

- No increase of any other toxic emissions
  CO, HC, NO, NO2, N2O
  Sulfates (desirable)
  PAH and Nitro-PAH
  PCDD/F

- Pressure Loss for loaded < 200 mbar
  New trap should be below 50

- Automatic dosing systems for fuel additives

- Electronic OBC with 2 Alarm Levels for
  trap clogging and trap damage

- Field control criterion: opacity < 0,24 1/m (0,033 g/m3)
  during snap acceleration (low to high idle)

- Noise
- Safety
- Size
- Investment and maintenance cost
- Service Interval
- + + + + + see Filter List

# Trap-System Certification Procedure

Basis Assumptions according to deep filter theory

- Trapping Efficiency is defined for solid particles
  "solid" when passing the trap
- Trapping Efficiency depends mainly on
  Volume flow and Temperature
- Trap-Systems may be tested on any Diesel engine
  at max. space velocity and temperature
- Trapping Eff. is equal for steady state and transient

→ Trapping quality can be verified on any represent. engine

Procedure:

- ISO 8178/4 C1: 4 operation points
- Fresh, loaded and cleaned Filter
- With/without fuel additives
- Steady state and snap on test
- Emission online during regeneration
- New and after 2000 hrs

Instrumentation:

- Standard emission instrumentation
- Particle number concentration (SMPS)
- Particle chemistry (PAS, DC) + Coulometry
- Filter cake analysis for metals, sulfate +…

Test shortened in case of introducing new technology on existing systems
Test extended if production of secondary emissions is to be expected

# Filter-List

- Lists all trap-systems which have successfully passed VERT Filter Suitibility Test VFT and VERT-Secondary Emissions Test VSET
- Now 18 systems on the list
- Updated every 6 month – actual list 1.Oct.2000
- on BUWAL and SUVA-Homepages and DieselNet
- A system will be put on the list after Test 1 “new state” If retest after 2000 hrs field is not be successful or not performed after latest 2 years the trap system will be taken off the list
- Retesting also becomes mandatory if 5 % of reported field controls are exceeding 0,24 1/m during snap on
- The List is widely accepted by manufacturers and users and has become the most important implementation tool

# How to measure engine emitted Aerosols

- **Health effect oriented**: Combine characterization of mass, surface, number, chemical composition
- **Transient :** time constant 1 sec to monitor emission peaks during ETC
- **Sensitive**: better than 0,5 g/m3 EC to use same method for emission and ambient
- **Robust :** to use same method for certification and field control
- **EC-oriented** for Traceability
- **At Tail-Pipe-conditions**: avoiding all condensatin artefacts by high/hot Dilution (D >1:100 / 150°C)

No satisfying method was available in 1995
Therefore BUWAL supported development of a new ETH-Aerosol-Research method NanoMet based on available

- High/hot dilution
- Mobility sizing
- Double–sensor technology PAS+DC

Instrument is now commercially available by Matter Engineering and has just successfully passed round robin test of German Occupational Health Authority

# How to calibrate particle measuring instruments

with respect to a leading chemical substance and traceability

- **EAM (Swiss Authority for Measurement) identified "Combustion Aerosol Metrology" as the most important metrology target in 1995**

- EAM started consequently to develop an Combustion Aerosol Standard to be used for official calibration of any instruments offered by manufacturers

- CAST (Combustion Aerosol Standard) is now available

- Principle: perfectly controlled diffusion flame combustion

- Composition of particles is > 98 % EC

- Size of Particles is available 20 – 500 nm

- Concentration can be adjusted by dilution
  3 orders of magnitude variation

# Field control for Trap-Systems

**Actual Use:** **mobile Opacimeter**
**n**ot very sensitive
but good enough to identify trap damage
for given engine emission quality
widely available in Switzerland
because of onroad legislation

However Opacimetry does not monitor ultrafine particulate emission and will not be sufficiently sensitive for future engines

**Future :** **NanoMet**
Identifies trap efficiency by simultaneous transient measurement upstream and downstream during snap-on acceleration
and
can monitor ambient effect (threshold control) with the same instrument

# The Trap Manufacturer Association AKPF

A working group of actually 20 trap-system manufacturers (D, S, A, F, NL, UK, CH, USA, CAN )
with the following activities:

- Prepare technical standards
- Analyse Field experience
- Dialog with Authorities
- User-Information
- Define research topics
- Support new metrology

AKPF has become a very important dialog-partner for the swiss authorities.
Common meetings every 6 month
Information is public
Homepage under DieselNet by end of 2000

# Nanoparticle-Measurement-Conference

Yearly since 1997 at Zürich

- **Worldwide participation : 160 participants in 2000**
- **53 Papers and and 3 Workshops 2000**
- **3-day-meeting**
- **Proceedings available on CD**
- **No Conference Fee**
- **Next conference: 9/10 August 2001**
- **Call for papers in May**
  to get real updated information

The NMC is actually the only worldwide meeting of the Nanoparticle Measuremnt Communtity in Science and Engineering strictly oriented to characterization of combustion aerosols

# Trap-Retrofit Statistics and Field Results

- **2400 Traps in use in Switzerland**
  - 78 on trucks
  - 689 on buses
  - 800 on construction machines
  - 589 on fork lifts
  - 81 on stationary engines
  - 118 on rail and ships
  - 28 for periodic use (garages)

It is expected that this numbers will double in 2001

- **Failures:**
  - total failures over 10 years: 154 (0,6 % ?)
  - total failures after 1995 : 84
  - excluding unsuccessful test series : 56 ( 2,6 %)

Target is < 1 %

- **Emission Measurements in the Field in 2000**
  - 207 measurements (unsufficient)
  - Complains (exceeding 0,24 1/m) : 37 total
    excluding test series: 7 ( 3,3 % )
    Repair target: 10 days

# Particulate Trap Retrofit for all swiss onroad HDV

"Postulat STUMP"

A request on parliament level Mai 1999
Accepted by the Swiss government August 1999
Study on Feasibility concluded August 2000
Decision expected in spring 2001

- **66'000 HDV onroad**
- **Trap Retrofit justified for new (EURO 2) and up to 20 years old vehicles**
- **Cost in the Range of 5'000 – 12'000 SFR**
  Financing model by emission dependent road tax LSVA in force 1.Jan 2001
- **Pilot-Series (12 x 100) starting in 2002 proposed**
- **Feasibility investigated based on in-service statistical analysis of operational behavour for 12 Vehicle classes**
  (see SAE-Paper 3/2001)
- **Report on Feasibility available on CD**

# Available Documentation

- VERT-Reports (partly English) on 4 CD
- Swiss offroad inventory and prediction model on CD
- Swiss Legal Regulations (in German, French and Italian)
- Filter-List (with Specification and Certification Procedure) on CD
- Certification Reports VFT and VSET on CD (2 examples)
- Particle-Metrology (NanoMet) on CD
- Trap OBD-control (LogLink) on CD
- Calibration of Nanoparticle Instruments on CD
- NanoMet-Conference-Proceedings on CD
- Trap-Manufacureres : AKPF – Homepage
- Report on “Retrofit all swiss HDV” on CD

# CONCLUSIONS

- Particulate Traps are the only available measure
  To reduce solid combustion particle emission sufficiently
- Trapping efficiency can be as high as 99 %
- Reliable Trap systems are available
- Retrofitting traps is possible for all HDV
  with very few exceptions
- Fuel Sulfur Level should be as low as possible < 10 ppm
- Lubrication Oil TBN should be low and ash should be low
- Electronic OBD is a must
- Systems must operate fully automatic
- Systems can be designed to avoid all secondary emissions
- Frequent field control is recommended
- Certification Procedure must include solid particle number concentration and particle chemistry

Weitere Folien optional

# Possible Improvements of the gravimetric Method

- **Suppressing dew point effects**
  Sampling temperature > 100 °C
- **Increasing dilution Ratio**
  Coming closer to real word conditions
- **Avoid re-entrainment confounding**
  By use of 1µ-cyclon
- **Avoid confounding by fuel and oil-effects**
  Use clean substances for certification

# Remaining deficiencies

- no Substance-specific information
- no Aerosol-specific information
- no information on transient effects
- unsufficient sensitivity
- no agreement with ambient measurement
- calibration doubtful (just mass but which )

# Basic principles of Measurement

1. **No change of Mass, Phase and Composition between taking an sample and measuring its properties**
   any change during measurement process is artefact
   if artefact happens the measurement is not valid

2. **Object to be measured must be defined**
   Definitions of mixed substances like
   SOx = SO2 + SO3,
   NOx = NO + NO + N2O
   COx = CO + CO2
   PM = Soot + Ash + Sulfates + Water + Engine Wear
   can not properly be handled and lead to useless information

3. **Sample Conditions must be defined**
   Sampling in the engine, before TC, after TC
   at the tailpipe, in the dilution tunnel , at road side
   gives different results
   Conventions are needed

4. **Properties to be measured must be defined**
   PM or EC or TC or ……
   Cumulative mass or individual mass ?
   Mass or Surface or Number or ……?
   Aerodynamic Diameter of Mobility Diameter ?
   Substance of which the properties should be measured.

5. **Accuracy target must be defined**

6. **Calibration must be possible**

7. **Traceability should (must ?) be possible**

If we have no agreement on these basic principles
we better stop talking about measurement of
Diesel Particulate Emission

CARB Diesel Retrofit Advisory Committee – Meeting 3.November 2000

# Deficiencies of Legislated Gravimetric Particulate Matter Measurement Procedure

"anything downstream of an engine in an exhaust gas/air-mixture
found at 52 °C on a filter paper at undefined humidity and undefined dilution"

- **Does not mimic real world conditions**
  Insufficient dilution
  Dew point effects not excluded

- **Modifies and falsifies the substance**
  Formation of condensates and artefacts

- **No Substance-specific information**
  Toxic substances and water have equal value
  ( 1 single water-droplet and 1 million lung penetrating
  PAH-coated solid soot particles are equivalent)

- **No Aerosol-specific information**
  No information on Particulate Size
  Underestimates particle number/surface effects

- **Physical Principal different from ambient Measurement**

No agreement with basic measurement principles

# Targets for new Diesel Particulate Measurement Technology

- **Health oriented information**
  Mass ? Number ? Surface ? Size ? Substance?
- **Size-Specific information**
  according to particle mobility
  size the range 10-1000 nm
- **Substance-specific information**
  differentiate between solid particles
  (carbon and ash) and condensates
- **Sensitivity better then 1 g/m3**
- **Time resolution 1 sec**
- **Physical principle identical for Emission (certification and in use compliance) and Immission (ambient)**
- **Traceability to EC**
- Repeatability
- Cost
- Size
- Handling

# Alternative methods / New Metrology Candidates

- **SMPS**: count
  mobility sizing + CNC

- **ELPI:** mass
  13 stages impaction

- **NanoMet:** count, surface, substance
  mobility sizing + double sensing

- **Aethalometry**
  BC equivalent to EC-mass

- **Coulometry**
  EC + OC
- **Laser Induced Incandescence (TIRE-LII)**
  EC primary particles

- **Multi-Wavelength Laser**

- **Light Scattering -Methods**

- **Quartz-Microbalance (TEOM)**

- **Mini-Moudi and other new impactors**

- **SEM and other picture-analysis methods**

# Strange Findings when measuring Diesel Particles

- Where mass is high, number is negligible
  Where number is high, mass is negligible
- Mass downstream trap > mass upstream trap
- Number downstream trap > number upstream trap
- Number changes fast depending on dilution
- Bimodal Size distributions with different substances
- Sensitivity to dilution and sampling temperature
- Artefacts due to sampling conditions
- Reduction of particulate mass but not count
-